CFD PREDICTION OF THE BEAGLE 2 MARS PROBE AERODYNAMIC DATABASE

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Presented at

Thermal and Fluids Analysis Workshop 2001

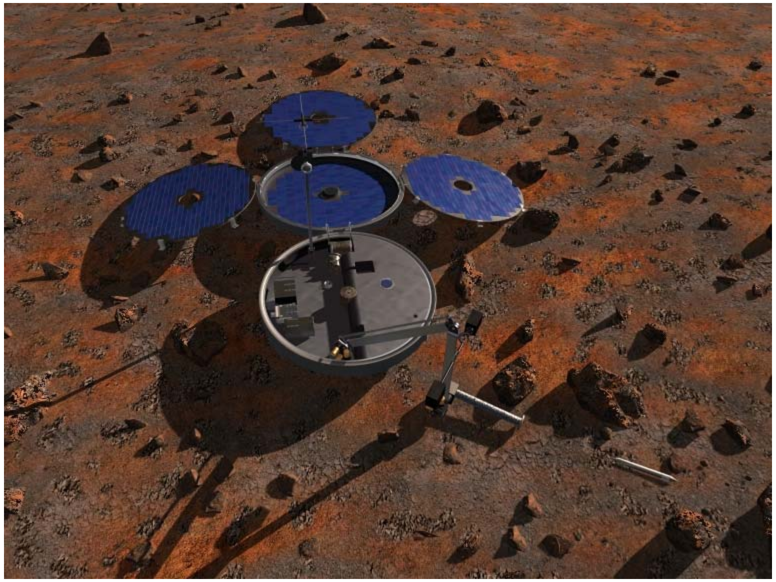
September 11, 2001

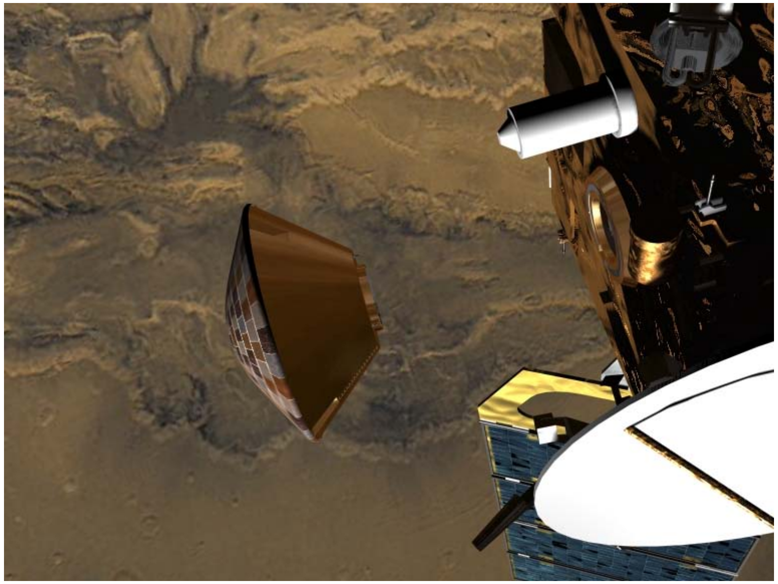
Overview

- Beagle 2 Mars Mission
- Aeroshell Design Approach
- Aerodynamic Database Approach
- CFD-FASTRAN Flow Solver
- CFD Analysis and Flow Features
- Static Aerodynamic Database
- Pitch Stability Analysis
- Summary

Beagle 2 Mission

- Beagle 2 Lander Part of ESA Mars Express Orbiter, Launch in June 2003
- Named After Charles Darwin’s Ship, HMS Beagle
- Martin-Baker Part of UK Beagle 2 Consortium
- Deliver Science Package to Mars Surface and Search for Signs of Life
  (Atmospheric Composition, Soil, Water, Organic Material)





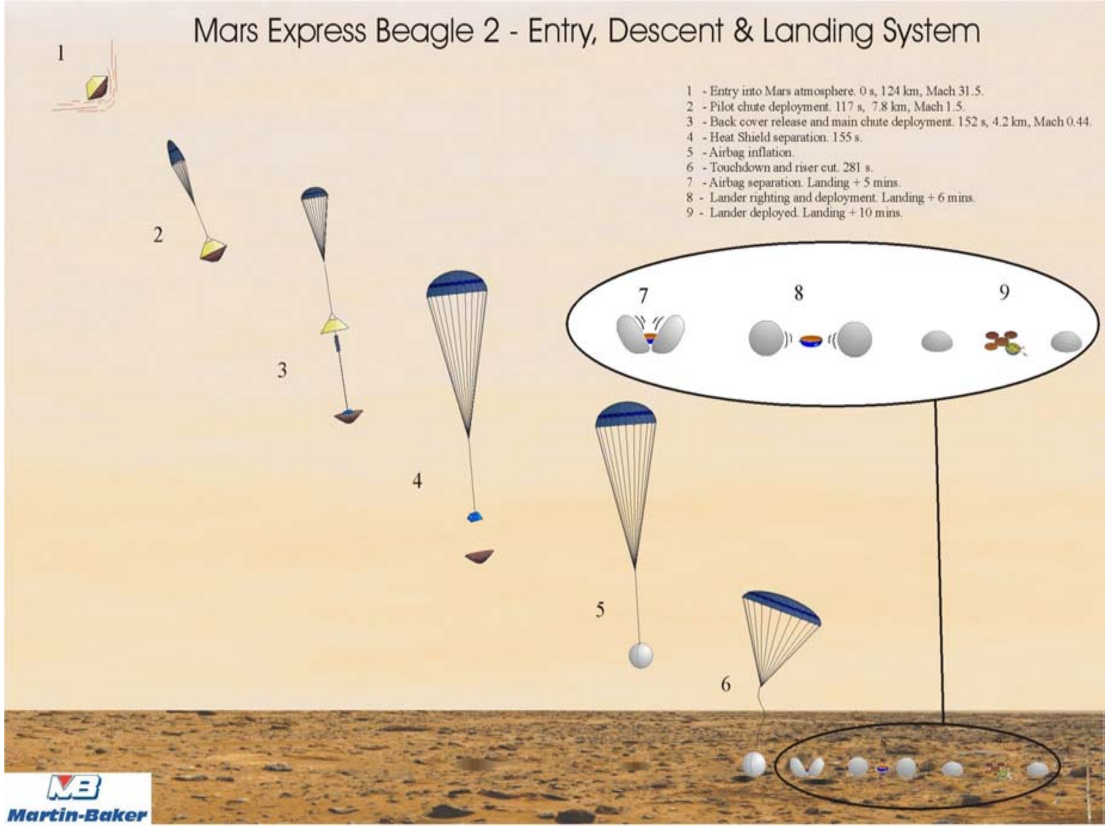
Martin Baker Role in Beagle 2 Program

- Martin-Baker Responsible for Beagle 2 Entry, Descent and Landing System (EDLS)
  - Entry Vehicle
  - Parachute Deployment
  - Transonic Deceleration
  - Aeroshell Separation
  - Airbag Inflation
  - Landing
  - Airbag Release

- Previous Experience Developing Cassini/Huygens Descent Control System

Beage 2 EDLS

- Beagle 2 Ejected From Mars Express 5 Days Prior to Entry
- Enters Atmosphere at Mach=31.5, Altitude=120km
- Aerobraking to M=1.5 Where Pilot Chute Deploys
- Main Chute Deployed at M=0.4
- Airbag Inflation
- Landing and Deployment of Experiments



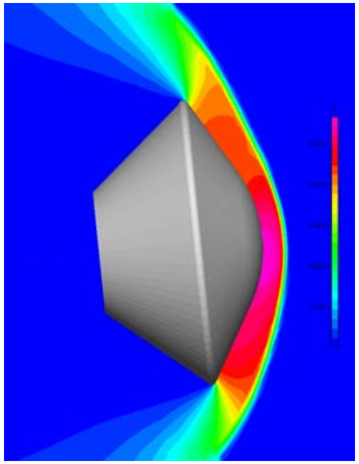
Beagle 2 Aeroshell Design Approach

- Simple Generic Shape to Take Maximum Advantage of Existing Aerodynamic Data, and to Simplify Analysis
- Use of Existing Aerodynamic Databases (Huygens, Stardust, Viking, Pathfinder)
- Adoption of ballistic entry
- Minimum ballistic coefficient
- High Drag Shapes Consistent with Stability Constraints and Existing Databases (Large Angle Sphere Cone)
- Nose Radius For Minimum Mass, Maximum Drag
- Minimum Corner Radii for Maximum Drag, Limited by Structural/Thermal Requirements
- Base Diameter Maximum for Minimum Ballistic Coefficient

Beagle 2 Aeroshell Design Approach

- Constraints on Project Budget and Time to Launch Opportunity
- Reuse Existing Database
- Limited Wind Tunnel Experiments
- Apply CFD to Develop Transonic-Supersonic-Hypersonic Aerodynamic Database
- Develop Blended Aerodynamic Database From Existing Scaled Data, CFD Predictions and Wind Tunnel Experiments

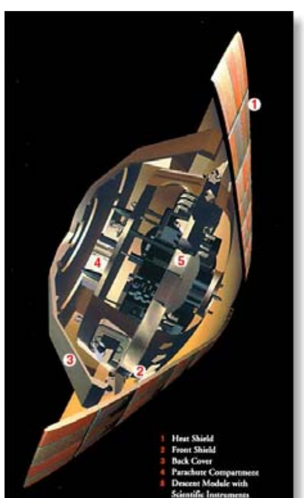
Role Of CFD In Beagle 2 Development



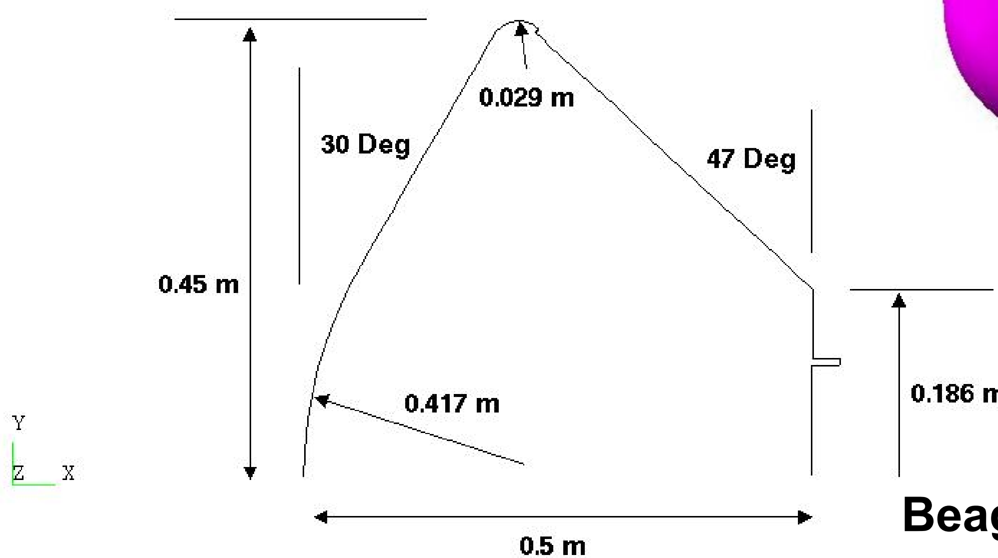
- CFD Now Mature Enough for Reliable Use for Entry Bodies
  - Reduction of Wind Tunnel Testing Costs, Time Savings
- Martin Baker Utilize CFD-FASTRAN for Entry Body Flow Prediction
  - Static Aerodynamic Coefficient Derivation
  - Localized Flow Effects
  - Heat Flux
  - Dynamic Coefficient Derivation
- US Navy, CFDRC, and Martin-Baker Have Used CFD for a Wide Range of Escape System Related R&D
  - Seat and Occupant Aerodynamic Database Development
  - Evaluation of Seat Stability Enhancements

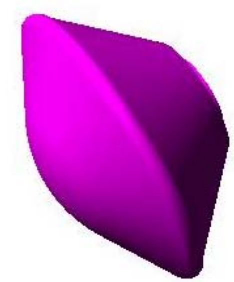
Beagle 2 Aeroshell Geometry

- Geometrically Similar to Huygens Probe
  (To Maximize Data Reuse From Huygens Program)
- Addition of Backshell Frustrum Enclosing Payload
- 60° Half Angle Blunted Cone
- Maximum Diameter D=0.9m (Huygens D=2.7m)
- Mass 60kg (17% Science Payload)



Huygens



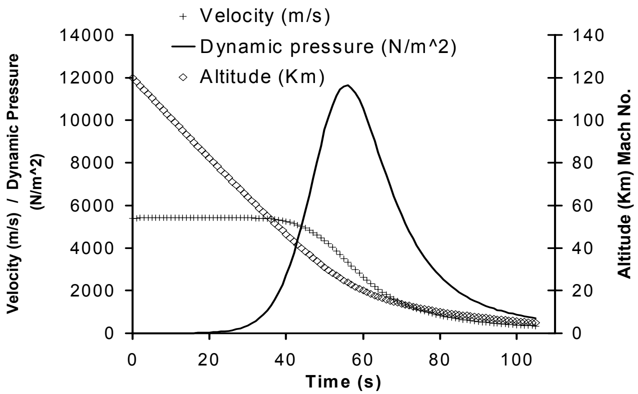


Beagle 2

Beagle 2 Aerodynamic Database Matrix

CFD Database Matrix selected from Nominal Trajectory

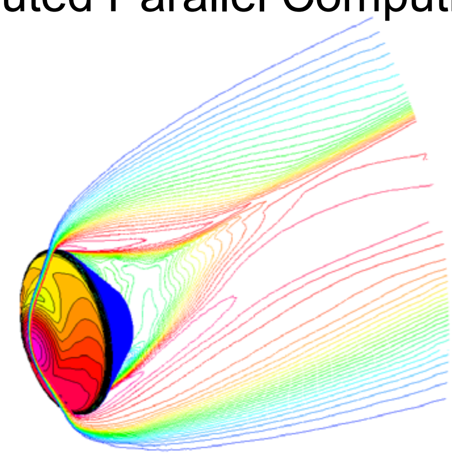
- Martin-Baker 6-DoF Trajectory Code
  - NASA MarsGRAM Atmosphere
  - Newtonian Aerodynamics
  - Derived Aerodynamic Databases
  - Monte Carlo Dispersion
- Nominal Trajectory
  - Entry Angle of γ = -18º
  - Altitude 120 km
- Nine Trajectory Points Selected for CFD Analysis

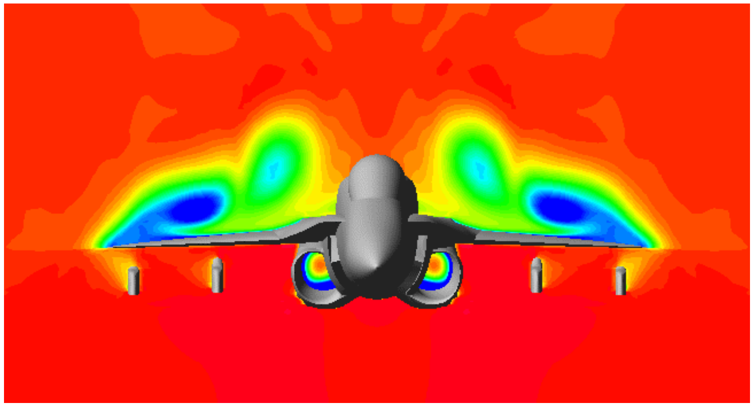


Mach No.	Velocity (m/s)	Temp (K)	Pressure (Pa)
28	5386	156.8	1.4
25	5061	170.8	8.9
20	4248	184.5	29.1
15	3256	191.1	59.3
10	2200	195.6	104.0
7	1552	198.3	144.9
5	1117	200.6	185.7
3	677	204.3	257.7
1.5	345	209.2	398.3

CFD-FASTRAN Flow Solver

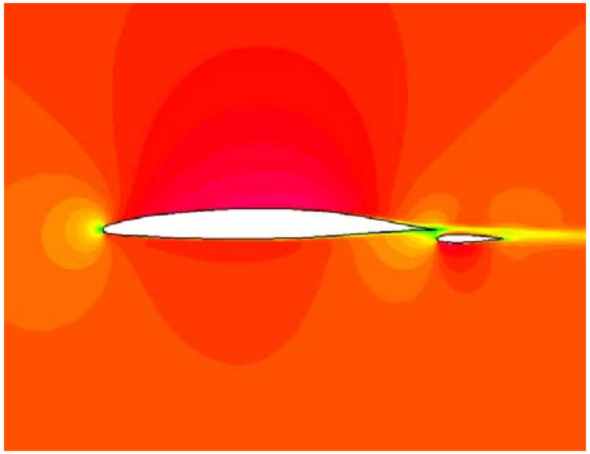
- Density-Based Finite Volume Formulation
- Euler and Navier-Stokes for 2D, 3D and Axisymmetric
- Multi-Zone Structured/General Unstructured/Hybrid Grids
- Chimera Overset Grids
- Laminar, Turbulent (Baldwin-Lomax, K-ε, K-ω, Spalart-Allmaras)
- Generalized Finite Rate Chemistry and Thermal Non-Equilibrium
- Roe Approximate Riemann Solver and Van Leer Flux Vector Splitting
- Explicit, Point Implicit and Fully Implicit Time Integration
- Distributed Parallel Computing Capability

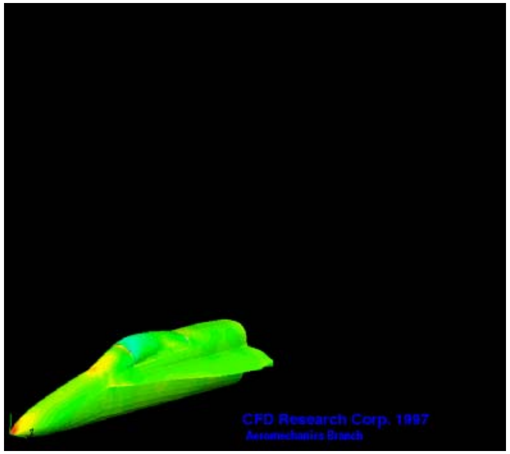




CFD-FASTRAN Multi-Body Dynamics

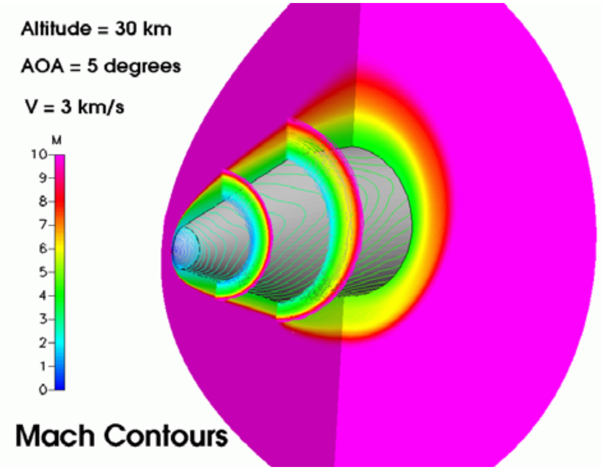
- Fully-Automated Chimera/Overset Grid Methodology
- Fully Coupled 6-DOF Solution for Multiple Body Motion
- Closed Loop Control Models Including Autopilot, Motor Ignition/Firing, Thrust Profiles, Point Forces
- Comprehensive Output of Forces, Moments, Angular Velocities, Accelerations and Body Orientations in any User Defined Axis System
- Easy-to-use GUI for Fast Model Set-Up (Physics, Chimera Hole Cutting)

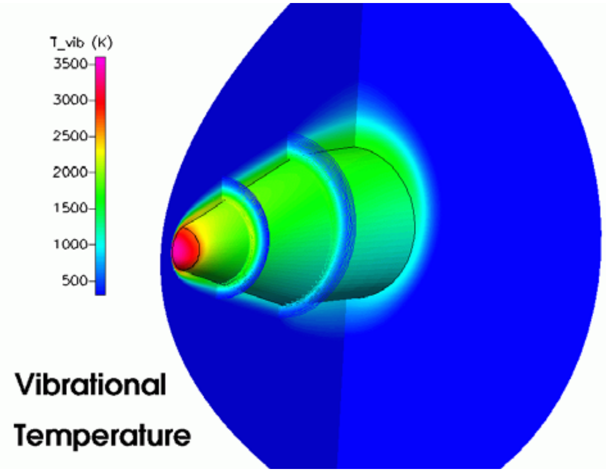




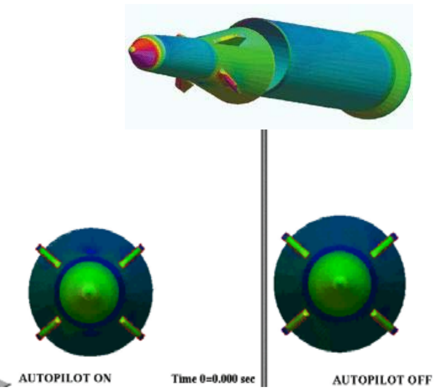
CFD-FASTRAN Thermochemistry

- Two Databases for Thermodynamics
  - Curve fit database for 300K to 6000K
  - Spectroscopic Database for Thermal Non-Equilibrium
- General Finite Rate Reactions
  - Handles Arbitrary Number of Species and Reactions
- Multiple Energy Modes
  - Thermal Equilibrium or Two-Temperature Non-Equilibrium
- Applications
  - Entry or Re-entry Physics
  - High Speed Missile Applications

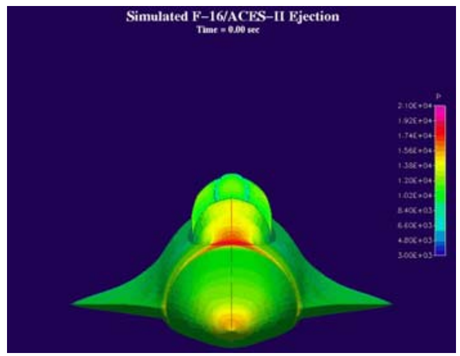




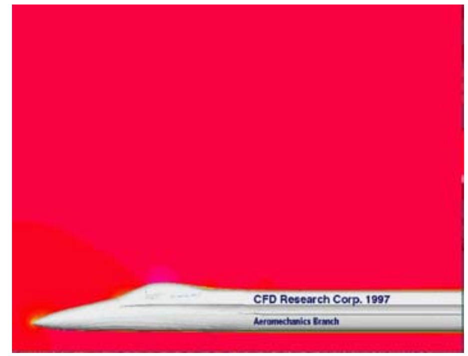
CFD-FASTRAN Applications



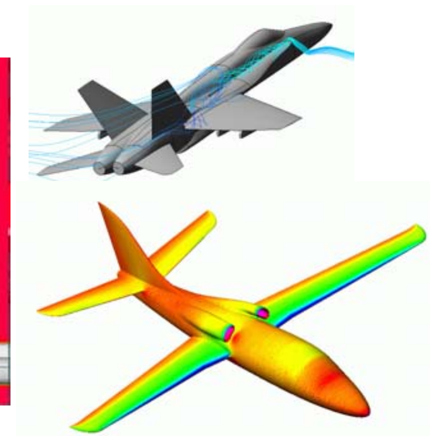
Missile Staging/Maneuvering



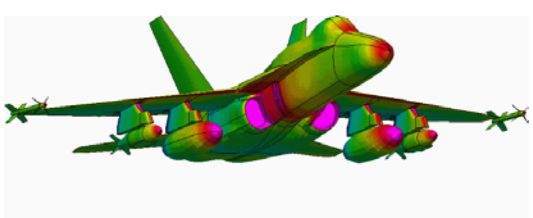
Escape Systems



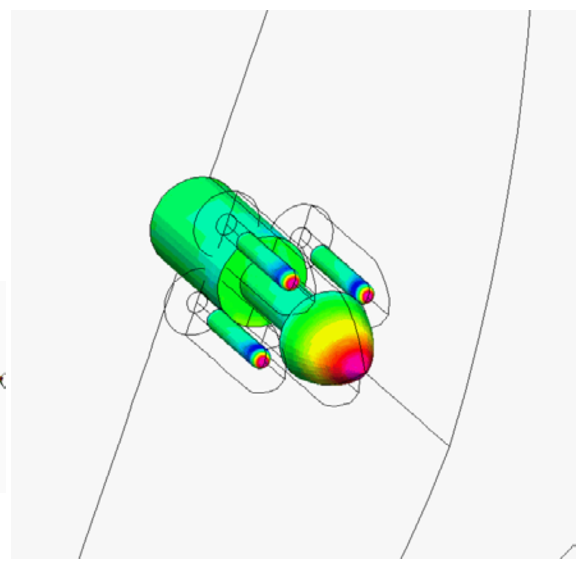
Canopy Trajectory



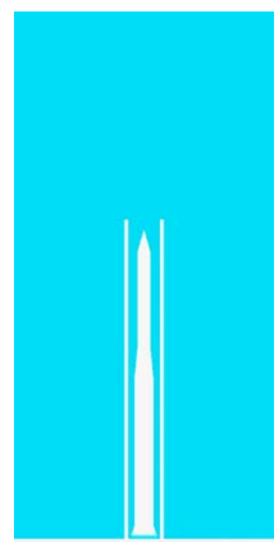
Aircraft Aerodynamics



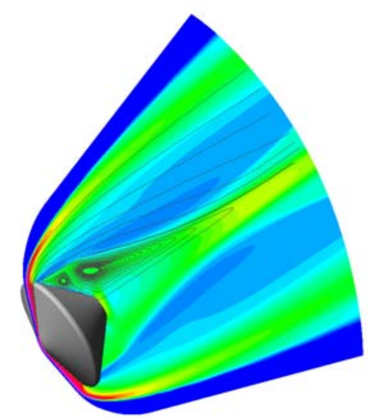
Store Separation



Ammunition Dispenser



Tube Launch



Aerothermochemistry

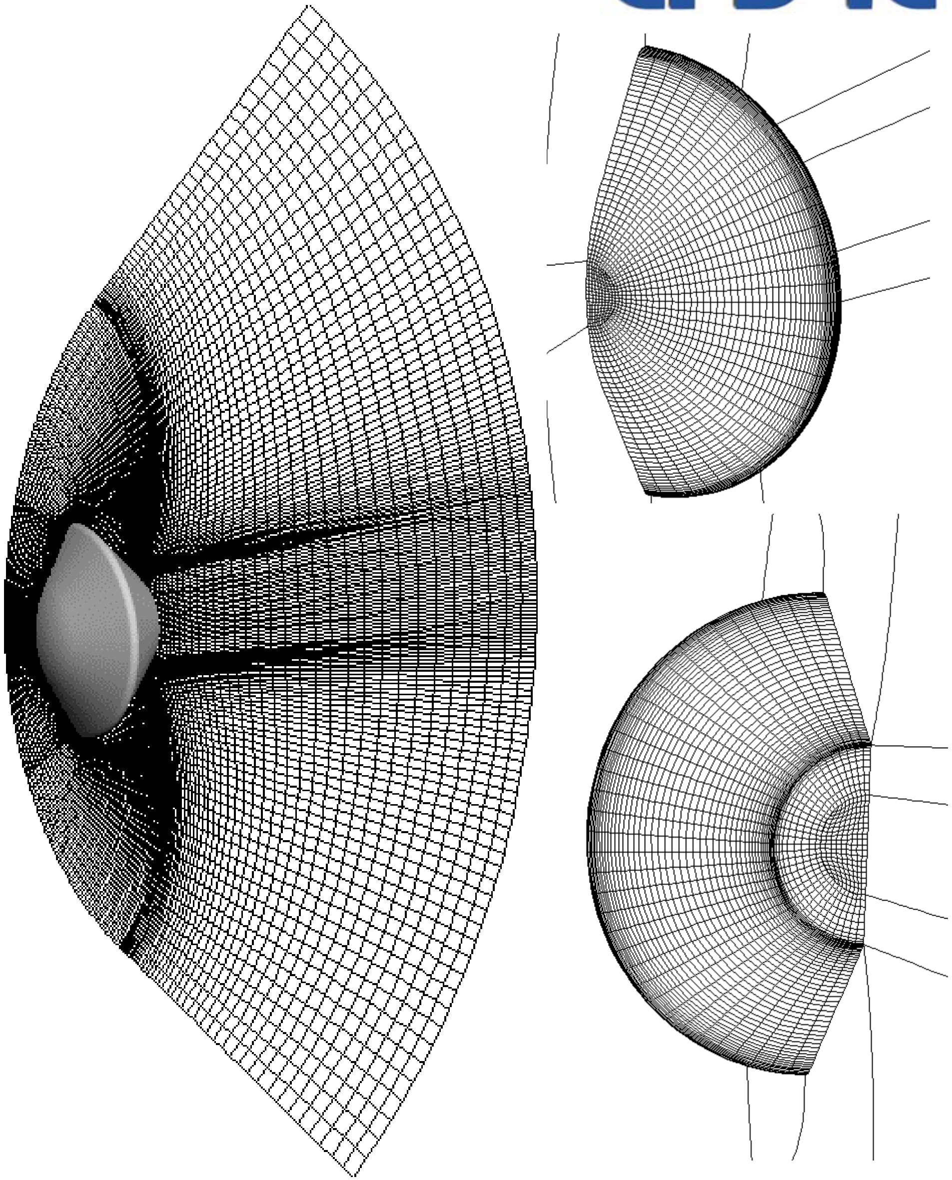
Mars Atmosphere CFD Model

- Laminar
- Fixed Wall Temperature
- Martian Atmosphere: 97% CO_2, 3% N_2 (Mass Fraction)
- Below Mach=7:
  - Nonreacting Mixture of Thermally Perfect Gases (CO_2, N_2)
- Above Mach=7:
  - Finite-Rate Chemical Reactions
  - Eight Species (CO_2, CO, N_2, O_2, NO, C, N, O), No Ablation Products
  - Nine Reactions (Park, 1994)
- Analyze Reacting and Nonreacting Cases at Mach=7 to Verify Consistency

Mach No.	Angle-of-Attack (Degrees) 0	2	5	8	11	Gas Chemistry
28		●	●	●	●	Reacting
25		●	●	●	●	Reacting
20	●	●	●	●	●	Reacting
15		●	●	●		Reacting
10		●	●	●		Reacting
7	●	●	●			Reacting
7	●	●	●			Nonreacting
5		●	●			Nonreacting
3	●	●	●	●	●	Nonreacting
1.5	●	●	●	●	●	Nonreacting

Beage 2 Computational Grid

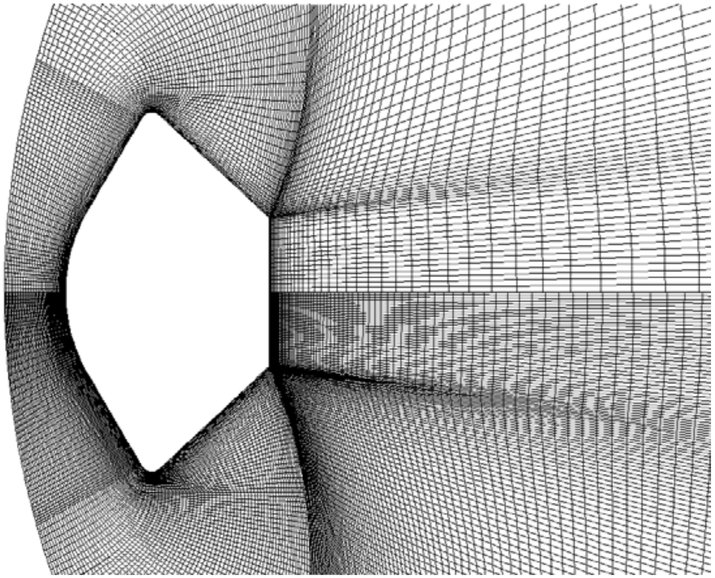
- Half Body Model (180 Degree), Assume Flow Symmetry
- Resolve Shock Layer and Wake
- Avoid Grid Singularities
- Hypersonic Grid: 305,000 Grid points, 9 Domains.
- Transonic Grid: 507,000 Grid points, 9 Domains
- Near Wall Grid Clustering With y^+ Range of 1.0 to 5.0



Beagle 2 Grid Refinement Study

Axisymmetric Grid Refinement Study to Ascertain Grid-Independent Solution for Aerodynamic Forces

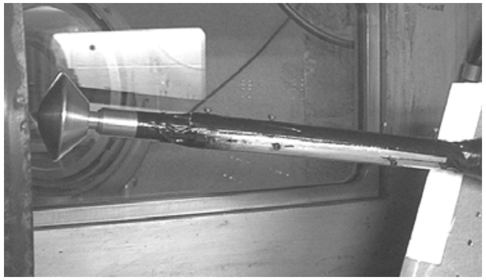
	Grid Density	C_A
Mach = 3 Nonreacting	Axisymmetric, Baseline Grid	1.5094
	Axisymmetric, Refined Grid	1.5095
	3-D, Baseline Grid, α=0°	1.5085
Mach = 20 Reacting	Axisymmetric, Baseline Grid	1.4598
	Axisymmetric, Refined Grid	1.4600
	3-D, Baseline Grid, α=0°	1.4596

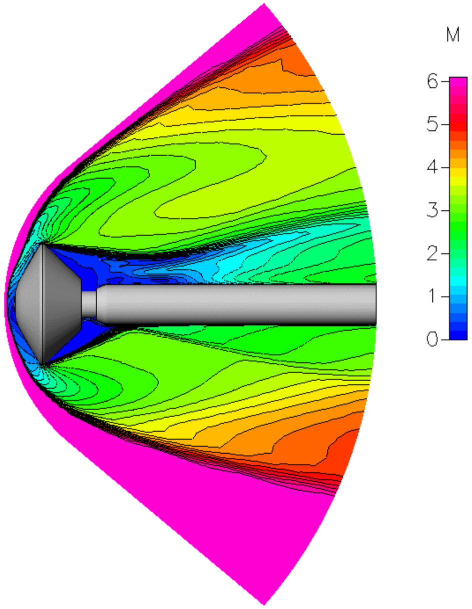


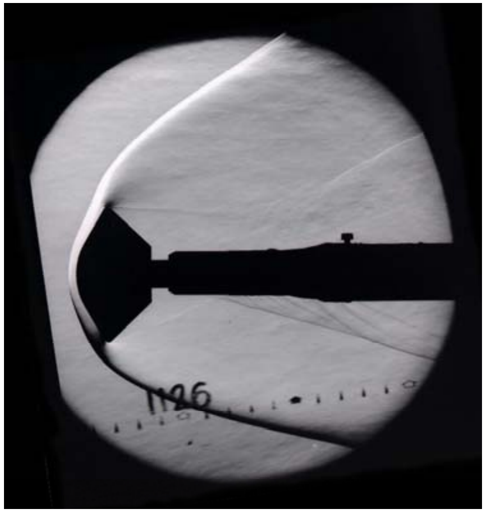
CFD Validation Against Experiment

Validation of Aerodynamic Force Predictions Against Experiment

- 60 mm Diameter Beagle 2 Model
- Oxford University Gun Tunnel
- CO_2 gas
- Mach=6

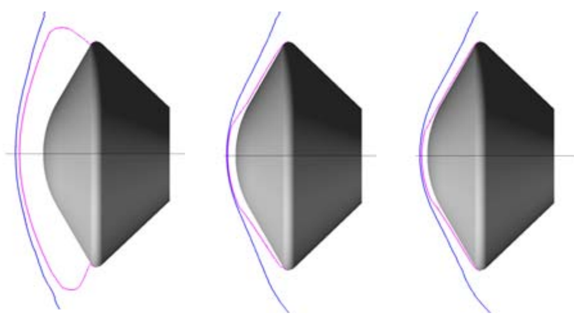


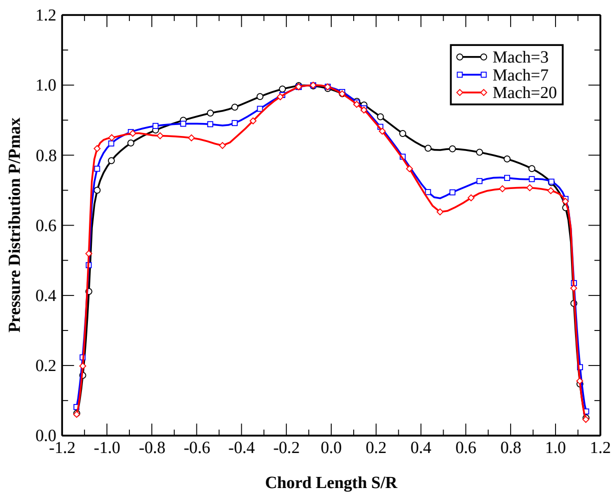




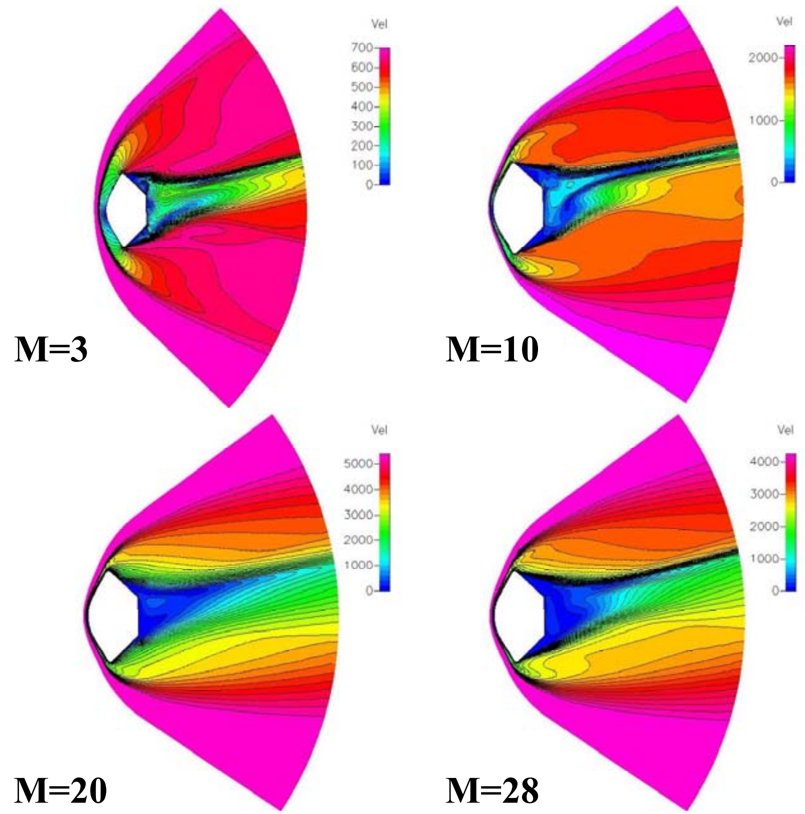
Beagle 2 Flow Field Characteristics

Aerodynamics Affected by Shift of Sonic Line, Effect of CO_2 Gas



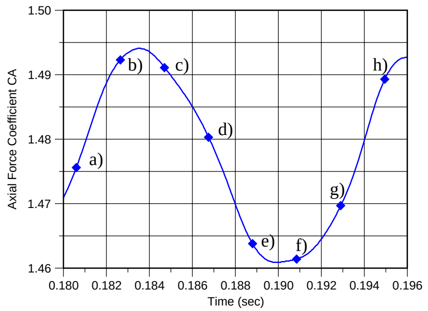


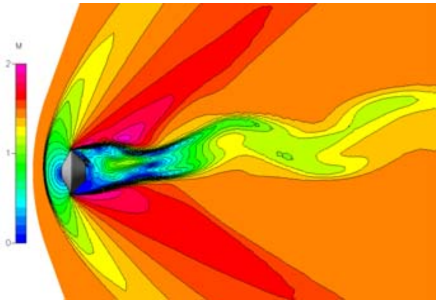
Evolution of Wake Over Trajectory: Reattachment Point Moves Forward



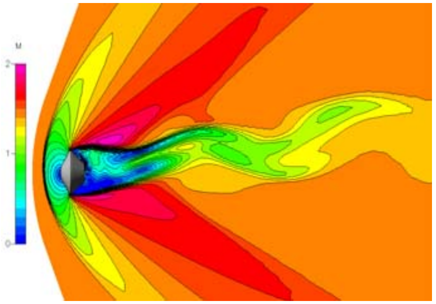
Beagle 2 Flow Field Characteristics

- Base Flow at Mach=1.5 Unsteady
- Oscillations Result From Interaction of Separated Shear Layer and Strong Reverse Base Flow

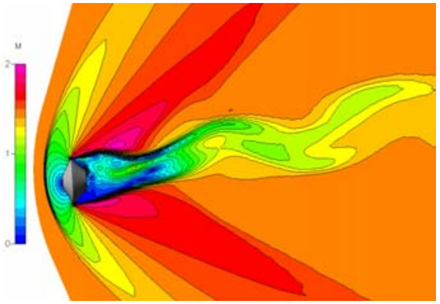




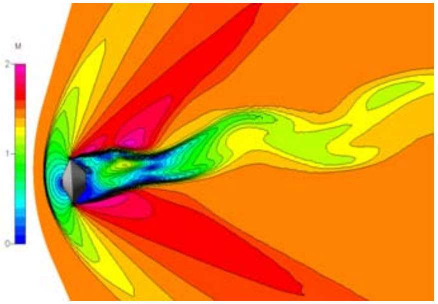
(a) time = t_o



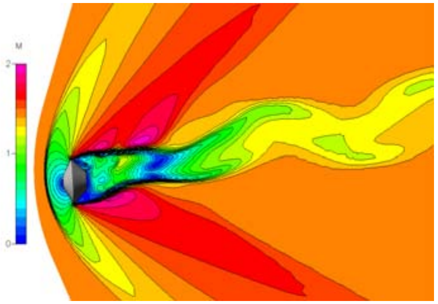
(b) time = t_o + 0.002 sec



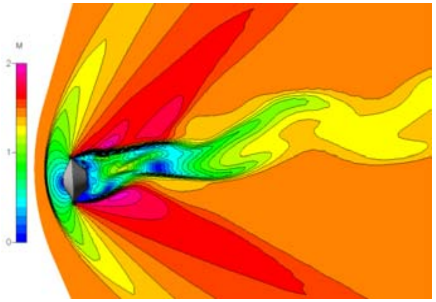
(c) time = t_o + 0.004 sec



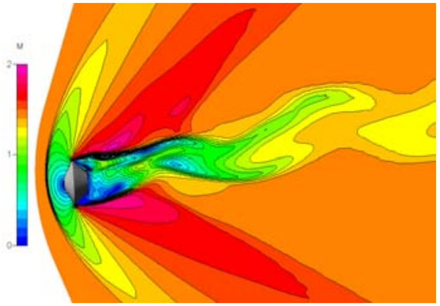
(d) time = t_o + 0.006 sec



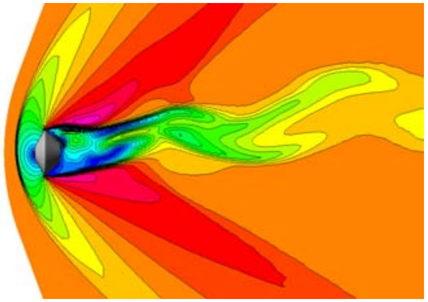
(e) time = t_o + 0.008 sec



(f) time = t_o + 0.010 sec



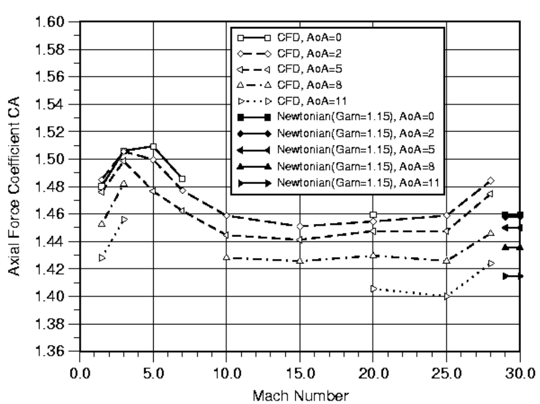
(g) time = t_o + 0.012 sec

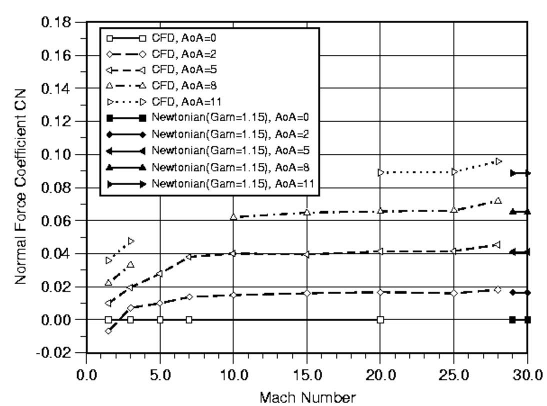


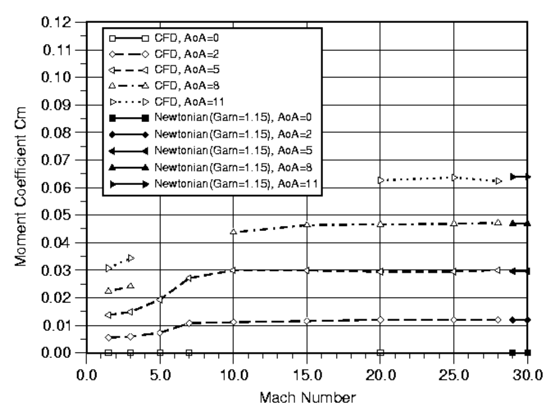
(h) time = t_o + 0.014 sec

Beagle 2 Aerodynamic Coefficients

- Newtonian Flow Approximations Hold Very Well for Mach Numbers Above 10
- Rise for Mach=28 Due to Transitional Flow (Knudsen Number=0.01)
- Below Mach 10, Transition to Half Newtonian Level for Normal Force and Moment Coefficients, Axial Force Components Rise Sharply
- Transition to Half Newtonian Level in CO_2 Occurs at Lower Mach Number Compared to Air





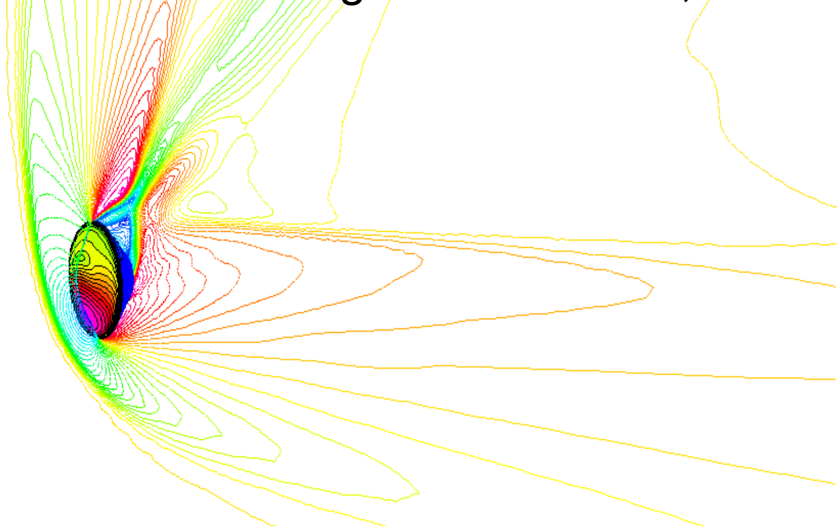


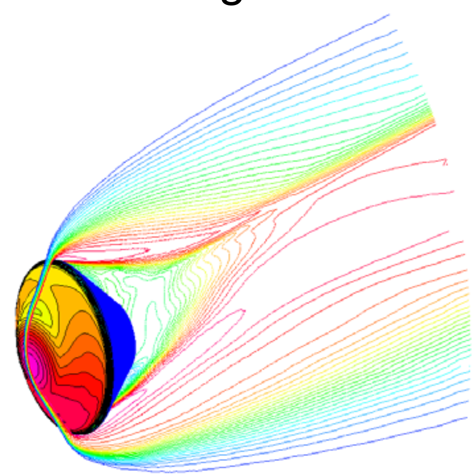
Beagle 2 Blended Database

Several Datasets Employed in Construction of Blended Database

- Current CFD Based Data
- Huygens Phase A2 Data, Scaled to Beagle 2 (Air)
- Huygens Wind Tunnel Data (Air)
- Stardust Sample Return Capsule Wind Tunnel and CFD Data (Air)
- Mars Pathfinder Data
- Scaled NASA Experimental Data for 60^{o} Cone (Air)

Total Angle of Attack Range from 0 to 30^{o}, Mach Number Range from 0.4 to 28.





Beagle 2 Dynamic Stability Database

Assess Stability of Beagle 2 at Pilot Chute Release

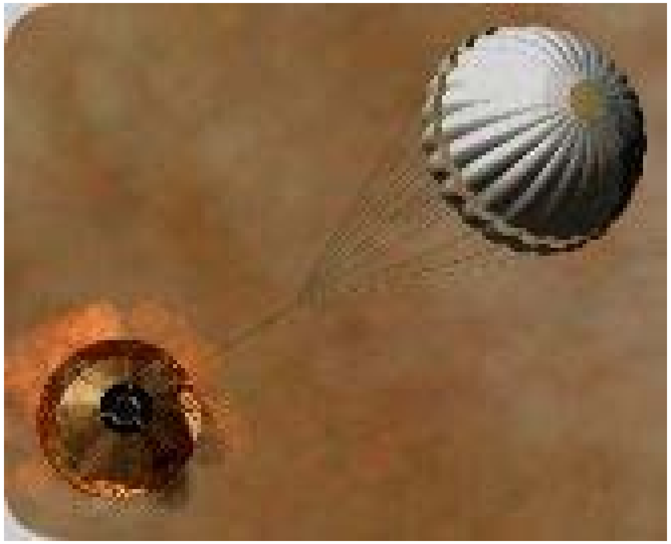
- Well Known Pitch Instability of Blunt Bodies in Transonic Regime
- Dynamic Behaviour Driven by Unsteadiness in Base Region
- Dynamic Instability Likely to Occur Near Pilot Chute Deployment, M >1.5

Wind tunnel tests:

- Oxford University CO_2 Tunnel, Mach=2

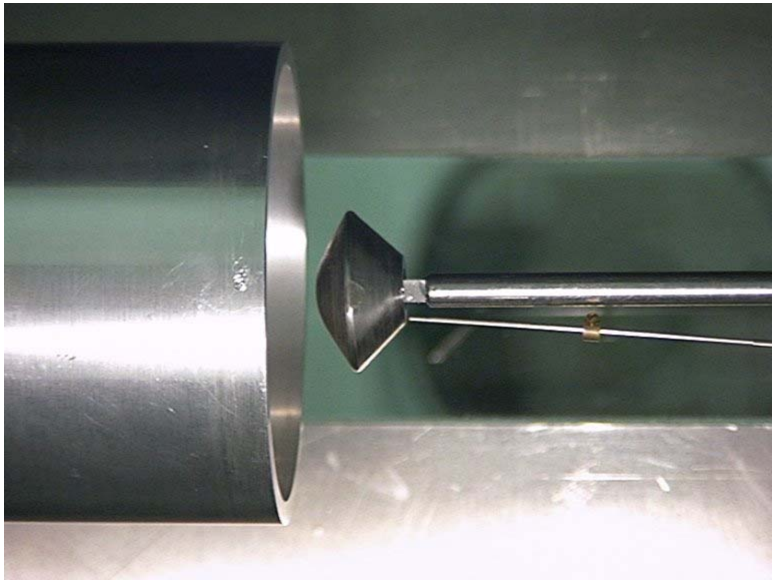
CFD Analysis

- CFD-FASTRAN, Time-Accurate, 6-DOF



Beagle 2 Pitch Stability Experiment

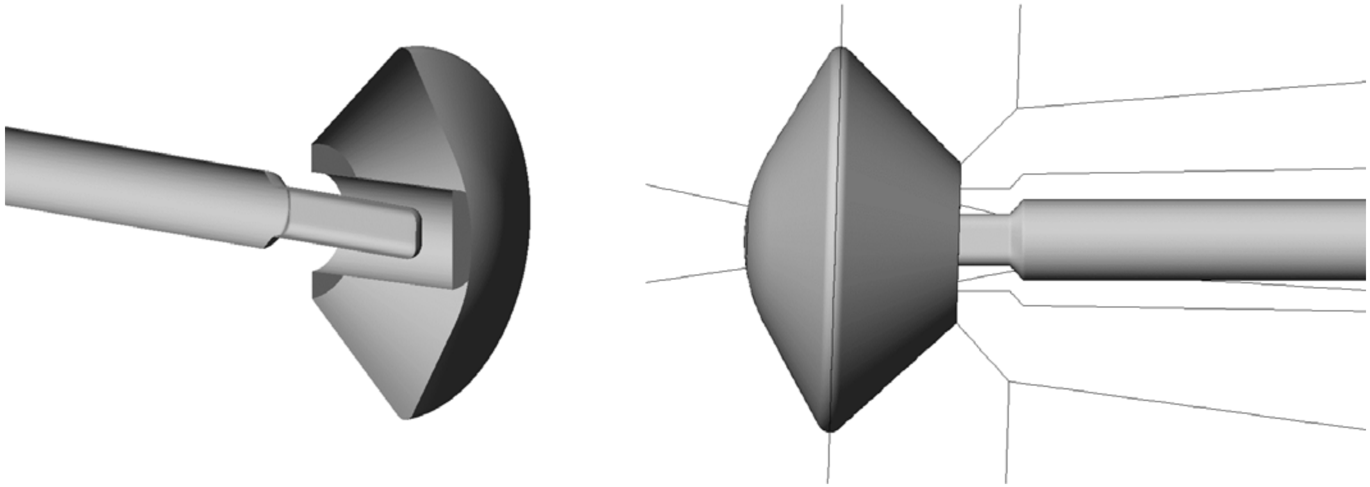
- Oxford University Tunnel
- Mach=2, CO_2 Gas
- Model 20 mm Diameter
- Run Time Greater Than 10 sec
- Mounted on Flexible Pivot
- AoA Perturbation by Push Rod
- Model Movement Measured by Accelerometers



CFD Pitch Damping Analysis

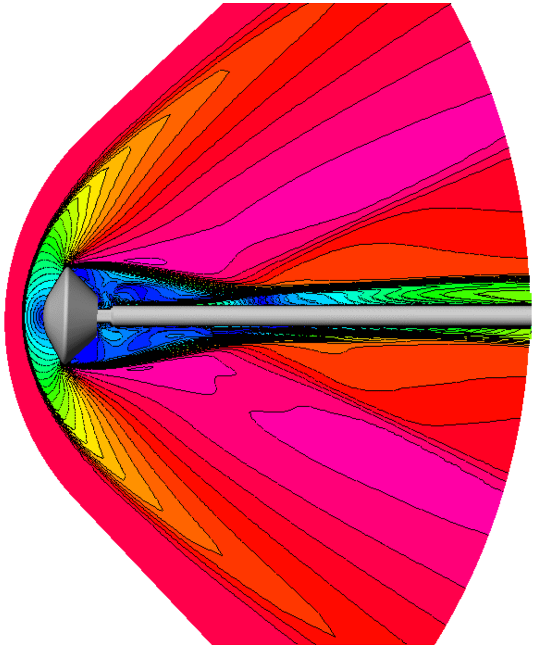
CFD-FASTRAN Calculations

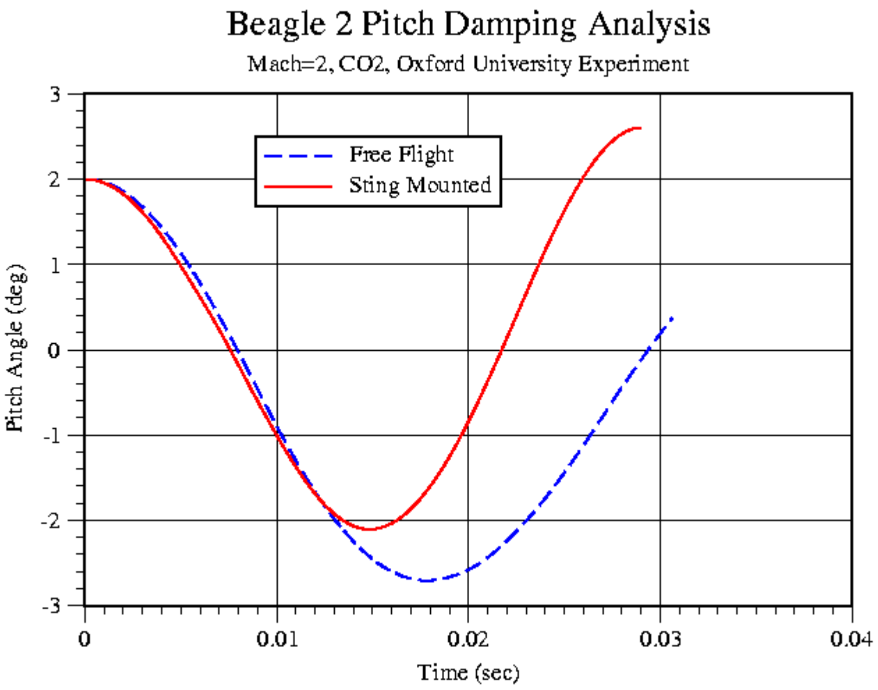
- Time-Accurate, 6-DOF (Constrained to Pitch Motion Only)
- Chimera Overset Grids: Sting Fixed, Model Moving
- Flexure Mount Resistive Torque Modeled
- Mach = 2, CO_2 Gas
- Initial Perturbation $\Delta\alpha$ = 2 Degrees
- Modeled Sting/No-Sting Configurations to Assess Sting Interference Effects



CFD Based Pitch Damping Results

- Pitch Damping Analysis is <u>Work in Progress</u>
- Insufficient Data Available to Extract Damping Coefficients
- Significant Effects of Sting Interference and Flexure Mount





Summary

- CFD Has Matured to Provide Reliable Planetary Entry Vehicle Aerodynamic Predictions
- CFD Provides Substantial Time And Cost Savings
- CFD-FASTRAN Applied Over Entire Trajectory (Entry to Chute Deployment)
- Valuable Insight Gained Into Vehicle Flow Characteristics (Examples: Wake and Base Flow Structure,Transonic Wake Unsteadiness)
- Blended Aerodynamic Database Generated by Combining CFD Data, Scaled Existing Data, and Wind Tunnel Test Data
- CFD Based Pitch Damping Analysis Provides Insight Into Dynamic Stability Characteristics Not Easily Obtained From Wind Tunnel Tests